THE OPTICAL SPECTRUM OF VELA X

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Summary

The optical spectra of two filaments in the nebula Stromlo 16 (the radio source Vela X) were obtained with the photoelectric spectrum scanner. Electron temperature stratification over the filaments has been deduced from the intensity ratios between certain lines in these spectra. Indications are of a small-sized high temperature region with an electron temperature $T_e \simeq 10^5$ °K together with a much greater volume of cooler gas with $T_e \simeq 10^4$ °K. The former region is bright in the lines of OIII whilst the latter region is bright in the lower excitation lines of OII, NII, and H. The collisionally excited nature of these spectra confirms previous conclusions that this object is the remnant of a supernova.

I. Introduction

In a previous paper (Milne 1966) evidence was given for accepting Vela X (Stromlo 16) as a supernova remnant. One of the points raised but not fully discussed was the stratification of the electron temperature in the filaments. It is the purpose of this paper to present the observations and deductions leading to this conclusion.

The filamentary nebula Stromlo 16 covers an area about 4° by 2° centred on right ascension $08^{h}\,32^{m}$ and declination −45°. It is composed of a faint background emission over most of this area with many bright sharp filaments around its northern and western boundaries and more diffuse nebulosities on the eastern face. This is illustrated in Figure 1, which is a mosaic composed of four plates taken with the Uppsala 26 in. Schmidt camera at Mount Stromlo. The exposures were each 120 min and were made on 103aE plates through an RG-2 filter.

II. Observations

The two bright sharp filaments indicated in Figure 1 were examined for line emission with the photoelectric spectrum scanner on the Mt. Stromlo 50 in. reflector. Most of the observations were made by integrating the signal received when the grating angle was set for the wavelength of expected lines and comparing this with the integrated signal each side of the line. Integrating times were 50 sec each, usually carried out in sets of three for each wavelength. The estimated total integration time for each line was of the order of 1 hr in filament "A" and somewhat less in the other filament "B". The entrance and exit slits were set at 2 mm, giving a triangular response of half-intensity width 18 Å; the projected angular resolution on the sky was then 18 sec of arc. A decker 15 mm long was used; the entrance slit was not rotatable and was fixed in the north–south direction in the positions shown in Figure 1.

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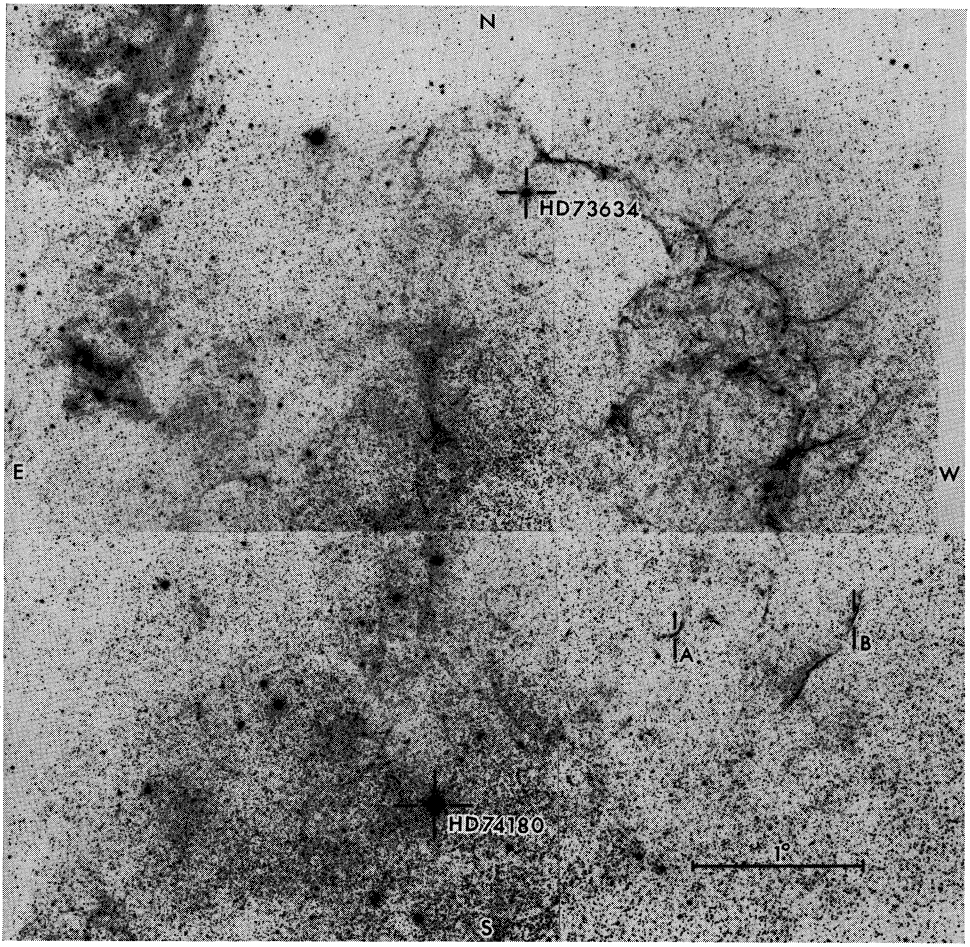

Fig. 1.—The filamentary nebula Stromlo 16 taken in Hα light. The positions of the entrance slit of the spectrum scanner on filaments "A" and "B" are indicated.

The scanner was equipped with a monitor cell (2P21), and either a 2P21 cell working in the second-order blue or a 7102 cell in the first-order red was used for the spectral measurements. The scanner response was determined from scans on ϵ Ori, whose monochromatic magnitudes are given by Oke (1964). Appropriate filters were used to cut out overlapping orders when making the stellar scans but were not used for the emission line measurements. Scans and integrations were made on the Orion nebula to calibrate the wavelength scale. Very little work was done in the red—the scanner sensitivity is severely limited and the nights chosen to use the red cell were not favourable.

TABLE 1

LINE INTENSITIES

(1) Line		(2) Multiplier Current (10^{13} A)	(3) Corrected for Scanner Response	(4) Corrected for Reddening
Filament A (R.A. $08^h 31^m$, Dec. $-45° 25'$, 1950·0)				
[OII]	3727 Å	518±40	285±22	322±22
?	4040*	35±10	19·1±5·5	22±7
[SII]	4070*	22±10	12·2±5·5	14±6
Hδ	4108	9±5	4·8±2·7	5·2±3
Hγ	4340	44±3	27·8±2	31±2
[OIII]	4303	21±5	13·7±3·3	51±4
Hβ	4861	60±7	100(±12)	100(±12)
[OIII]	4959	22±4	40·6±17	40±7
[OIII]	5007	49±8	100±16	97±16
[NI]	5200	7±5	18±13	17±13
[NII]	6548*	5±3	3000±1500	2600±1300
Hα	6563	5±2	3000±1000	2600±1300
[NII]	6588*	3±2	1800±1000	1600±900
Filament B (R.A. $08^h 25^m$, Dec. $-45° 15'$, 1950·0)				
[OII]	3727	960±60	590±37	670±50
Hδ	4102	< 15±15 (not seen)	< 9±9	< 10±10
Hγ	4340	54±15	38±11	42±12
[OIII]	4363	42±15	30±11	32±12
Hβ	4861	54±15	100(±28)	100(±28)
[OIII]	4959	72±15	115±30	114±40
[OIII]	5007	174±20	390±45	385±45

* These lines were only measured from scans. Other lines, except 5200 Å, were scanned and integrated; 5200 Å was not scanned.

Two spectral scans were made on filament A. These were used to confirm (roughly) the integrations and were the means by which the SII doublet at 4070 Å and the unidentified line at 4040 Å were found. These two features were present in both scans. The results of this investigation are given in Table 1. The errors shown in column 2 were arrived at for each line individually and depend on the observational method employed; they are generally standard deviations (where sufficient readings were taken). The errors were found to originate from two basic sources: a $\pm 8\%$ error in the reading due to instability of the sky transparency, and an absolute error in each reading of $\pm 10^{-12}$ A for the blue cell ($\lambda < 5500$ Å) and about $\pm 2\times 10^{-13}$ A for the red cell. Columns 3 and 4 of Table 1 are normalized to $I(\mathrm{H}\beta) = 100$; a reddening correction was applied proportional to $1/\lambda$ and normalized to $A_{\mathrm{v}} = 0\cdot 3\pm 0\cdot 1$ mag. This absorption was estimated from Velghe's (1963) colours and magnitudes of OB stars in this direction (see Milne 1968).

III. Electron Temperature in the Filaments

Estimates of the electron temperature of the two filaments observed depend on the following three basic approaches.

(1) Measurement of intensity ratios of lines of the same ion; these ratios do not depend on ionic abundances. This is applied to the Balmer lines and to the [OIII] lines.

(2) Determination of ratios of line intensities from different ions of the same atomic species, e.g. the [OIII] and [OII] lines. The relative gas masses and electron densities in the regions occupied by each ionic state must, however, be known.

(3) Lastly, relative intensities of lines originating from ions of similar ionization potential but different atomic species can be related to give the electron temperature of the nebula region where these ions mutually exist. The relative abundances must be known. This treatment is used for H, [OII], and [NIII] lines.

(a) [OIII] Lines

Following Seaton (1960) the relative population of the ^{1}D and ^{1}S levels of the O^{2+} ion is given by

$$\frac{N(^1\mathrm{D})}{N(^1\mathrm{S})} = \frac{5\cdot 4\times 10^{-3}\,\mathrm{e}^{-2\cdot 89/t}\,K\{1+0\cdot 12\,E+4\cdot 1\times 10^{-4}K(1+0\cdot 11\,E)\}}{1\cdot 16\times 10^{-5}\,\mathrm{e}^{-6\cdot 19/t}\,K\{1+3\cdot 8\times 10^{-2}K(1+0\cdot 10\,E)\}}, \tag{1}$$

where $E(\mathrm{O}^{2+}) = \mathrm{e}^{-3\cdot 30/t}$, $t = 10^{-4}T_{\mathrm{e}}$, and $K = 10^{-4}n_{\mathrm{e}}/t^{\frac{1}{2}}$, T_{e} being the electron temperature (°K) and n_{e} the electron density (cm^{-3}).

Equation (1) reduces to

$$\frac{N(^1\mathrm{D})}{N(^1\mathrm{S})} = \frac{4\cdot 65\times 10^{2}\{1+0\cdot 12\,E+4\cdot 1\times 10^{-4}K(1+0\cdot 11\,E)\}}{E\{1+3\cdot 8\times 10^{-2}K(1+0\cdot 10\,E)\}}. \tag{2}$$

Multiplying by the relative photon energies and transition probabilities, we arrive at an expression for the relative intensities in the nebular and auroral lines; namely,

$$\frac{I(\lambda 4959+5007\ \text{Å})}{I(\lambda 4363\ \text{Å})} = \frac{7\cdot 1\{1+0\cdot 12\,E+4\cdot 1\times 10^{-4}K(1+0\cdot 11E)\}}{E\{1+3\cdot 8\times 10^{-2}K(1+0\cdot 10\,E)\}}. \tag{3}$$

Equation (3) is displayed graphically in Figure 2. The shaded regions are outside the limit that the line ratio can assume as T_{e} approaches infinity and at an electron density too high for radiative [OIII] transitions (i.e. for n_{e} such that the spontaneous downward transitions are much fewer than the collisional depopulation of the upper level). The ratio of the fluxes in the nebular [OIII] lines $F(\lambda 5007\ \text{Å})/F(\lambda 4959\ \text{Å})$ is a well-determined value both theoretically (Garstang 1951) and observationally (Liller and Aller 1954). This ratio should be $3 \cdot 0$ and is independent of the exciting conditions. The value obtained for filament A was $2 \cdot 4$ and, for filament B, $3 \cdot 4$. The value $3 \cdot 0$ is included in the error limits, so no attempt has been made to adjust them to the theoretical value.

Proceeding with the assessment of electron temperature from the [OIII] lines, we have for filament A

$$\log\left\{\frac{I(\lambda 5007 + 4959\ \text{Å})}{I(\lambda 4363\ \text{Å})}\right\} = 1 \cdot 00 \pm 0 \cdot 1\,. \tag{4}$$

It may be seen from Figure 2 that this would yield an electron temperature in excess of $8 \times 10^4\,{}^\circ\text{K}$, provided the electron density is less than about 10^4 cm^{-3}. Temperatures lower than this are permissible only if the electron density is in excess of 10^4 cm^{-3}.

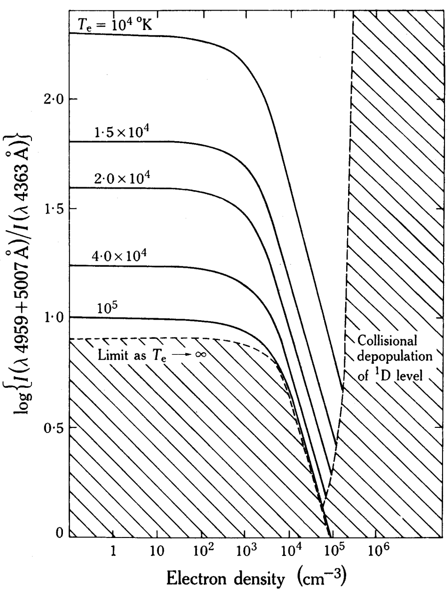

Fig. 2.—Dependence on electron temperature and density of the nebula and auroral line intensity ratio for OIII. The curves have been plotted from equation (3).

(*b*) *Hydrogen Lines*

The Balmer decrement obtained for filament A,

$$\text{H}\alpha : \text{H}\beta : \text{H}\gamma : \text{H}\delta = 26 \pm 13 : 1 \cdot 0 : 0 \cdot 32 \pm 0 \cdot 02 : 0 \cdot 06 \pm 0 \cdot 3\,,$$

cannot be satisfied by the radiative models investigated under various conditions by Baker and Menzel (1938), Capriotti (1964), and Pengelly (1964); the observed decrement is far too steep. A steep decrement is a feature of a collisionally excited nebula at a fairly low kinetic temperature, where the lower levels of the hydrogen atom are populated by electron collisions. As the electron temperature increases, ionization will result from the same mechanism and at about $T_e = 10^5$ °K, when the bulk of the gas is fully ionized, recombination and subsequent cascade will be responsible for most of the line emission. The Balmer decrement will then approximate the radiative excitation decrement.

Parker (1964*a*) has published calculations for collisionally excited nebulae, both for hydrogen lines and certain forbidden transitions. From a comparison of the observed decrement and Parker's data it would appear that an electron kinetic temperature of less than 10^4 °K is indicated. This estimate seems a reasonable one, although it depends critically on the Hα/Hβ ratio, which contains a very large degree of uncertainty. If the filament is optically thin in the Lyman lines, then the electron temperature could be a little lower.

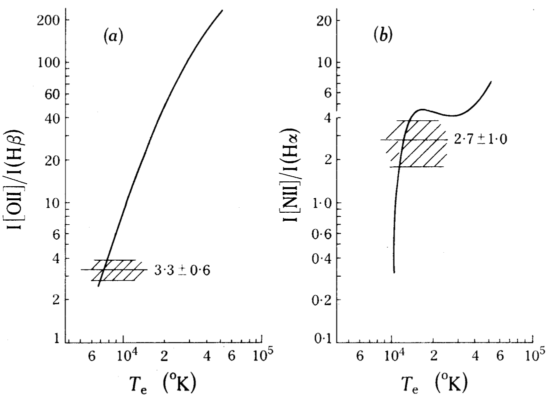

Fig. 3.—Temperature variation of the intensity ratios of the nebula lines of (*a*) OII to Hβ and (*b*) NII to Hα. The shaded strips enclose the values of these intensity ratios determined for filament A.

(*c*) [*OII*] *and* [*NII*] *Lines*

Figures 3(*a*) and 3(*b*) illustrate the temperature dependence of the intensity ratios $I(\lambda 3727$ Å$)/I(\mathrm{H}\beta)$ $(= I[\mathrm{OII}]/I(\mathrm{H}\beta))$ and $I(\lambda 6548 + 6583$ Å$)/I(\mathrm{H}\alpha)$ $(=I[\mathrm{NII}]/I(\mathrm{H}\alpha))$. The curves were drawn from Parker's (1964*a*) data assuming normal cosmic abundances (O/H $= 6 \times 10^{-4}$ and N/H $= 3 \times 10^{-4}$; Allen 1962) and electron densities in the range $200 \leqslant n_e \leqslant 1000$ cm^{-3}. The cross-hatched regions are the observed [OII]/Hβ and [NII]/Hα ratios for filament A ($3 \cdot 3 \pm 0 \cdot 6$ and $2 \cdot 7 \pm 1 \cdot 0$ respectively). The electron temperatures suggested by these data are about $7\text{–}8 \times 10^3$ °K in [OII] and $1 \cdot 1\text{–}1 \cdot 3 \times 10^4$ °K in [NII]. The temperature derived from the OII lines could be raised if the estimate of absorption at $\lambda 3727$ Å relative to that at $\lambda 4681$ Å were increased, either by an increase in the dependence of the reddening-wavelength law or by increasing the value of A_{v}. As an example of this, if a $1/\lambda$ reddening law were retained then a temperature of 10^4 °K would be indicated from the observed [OII]/Hβ ratio providing $A_{\mathrm{v}} = 1^m \cdot 12$, an absorption much higher than we estimate from Velghe's stars. The [NII]/Hα ratio is not affected by changes in the absorption, and even with the wide errors we have imposed on the intensities of these lines, a temperature above 10^4 °K is still indicated in the NII region. We deduce a slightly lower temperature from the observed [NII]/Hα ratio if a hydrogen temperature colder than that of the NII region is adopted—which is consistent with the slightly lower ionization potential of hydrogen compared with nitrogen.

These differences in electron temperature derived from the lower excitation lines of H, [NII], and [OII] and the higher excitation lines of [OIII] could be a real feature of this nebula if the shock fronts believed to exist in supernova remnants are responsible for the ionization and excitation of the filamentary gas.

(d) *Oxygen Doublets*

Estimation of the electron temperature from the oxygen doublets [OII], $\lambda 3726 + 3729$ Å, and [OIII], $\lambda 4959 + 5007$ Å, is straightforward enough if one assumes mixing of the ionic species. The electron temperature obtained for our observed ratio of $2 \cdot 5 \pm 0 \cdot 5$ would be about 4×10^4 °K, using Parker's data. This well-mixed model is not, however, a very realistic interpretation of our previous deductions. If we assume that the [OII] and [OIII] lines originate in regions of electron temperature 10^4 and 10^5 °K and have hydrogen densities n_{H1} and n_{H2} and volumes V_1 and V_2 respectively, we can write for the ratio of the [OII]/[OIII] intensity

$$\frac{I(\lambda 3726 + \lambda 3729)}{I(\lambda 5007 + \lambda 4959)} = \frac{(f_4 j_1^+ n_{\mathrm{H1}}^2 V_1) + (f_5 j_2^+ n_{\mathrm{H2}}^2 V_2)}{(f_4 j_1^{2+} n_{\mathrm{H1}}^2 V_1) + (f_5 j_2^{2+} n_{\mathrm{H2}}^2 V_2)}, \tag{5}$$

where it has been assumed that all the electrons are derived from the ionized hydrogen, and f_4 and f_5 are the ionization fractions at temperatures 10^4 and 10^5 °K respectively and j_1^+, j_2^+, j_1^{2+}, and j_2^{2+} are the volume emissivities of the lines from each ionic species and at each temperature. Using Parker's values for these and the ionization fractions at each temperature, we have

$$\frac{I(\lambda 3726 + \lambda 3729)}{I(\lambda 5007 + \lambda 4959)} \simeq 3 \cdot 65 \times 10^{-5} \frac{n_{\mathrm{H1}}^2 V_1}{n_{\mathrm{H2}}^2 V_2} + 5 \cdot 9 \times 10^{-3}.$$

Equating this to the observed intensity ratio for filament A, namely, $2 \cdot 5 \pm 0 \cdot 5$, we arrive at a density times mass ratio for the two regions of

$$\frac{n_{\mathrm{H1}}^2 V_1}{n_{\mathrm{H2}}^2 V_2} \simeq 7 \times 10^4 .$$

Dr. B. E. Westerlund (see Milne 1966) has estimated the electron density in filaments of this object to be 300 cm^{-3}. This estimate was made from the ratio of the line intensities in the [OII] doublet and is therefore applicable to the lower temperature region. This density compares well with densities obtained by Parker (1964*b*) for other supernova remnant filaments, and together with Parker's value for f_4 would yield a hydrogen density of 10^5 cm^{-3} for the low temperature region.

If we then consider that the [OIII] emission is generated in a region where $n_e < 10^4$ cm^{-3} (see Fig. 2), we will obtain a hydrogen density of $< 10^4$ cm^{-3} for this fully-ionized high temperature region, implying that the volume of this region is perhaps only 10^{-3} of the volume of the low temperature region, in order to satisfy the density times mass ratio of 7×10^4 above.

It is possible that the temperature stratification deduced here does not in fact exist. It would then be feasible to allow that an electron temperature of about 10^4 °K could obtain. However, this would require an electron density of near 10^5 cm^{-3} to give the observed ratio for the [OIII] nebula and auroral lines, which would conflict with the densities estimated from the [OII] doublet now required to originate in the same electron temperature and density field.

The above discussion was applied only to filament A; the observations were not so complete or accurate for filament B. The data obtained do, however, suggest similar stratification but with a lower temperature for the [OIII] region than that deduced from [OIII] in filament A—more like 5×10^4 °K with the lower excitation lines originating in a region of about $T_e = 10^4$ °K as before.

IV. Mass of the Filaments

Estimates have been made of the mass in the filaments A and B. These estimates were made from the Hβ intensities after calibrating the scanner response on the star ϵ Ori for which Oke (1964) gives a monochromatic magnitude of $1^m\cdot555$ at λ4861 Å. Using Code's (1960) value of $3\cdot8\times10^{-9}$ erg cm^{-2} sec^{-1} Å^{-1} for the flux corresponding to zero visual magnitude, together with a measured multiplier current of $1\cdot515\times10^{-7}$ A in an 18 Å band near λ4861 Å on ϵ Ori, an Hβ sensitivity for the scanner of $0\cdot108$ erg cm^{-2} sec^{-1} per ampere was derived. From Table 1 the multiplier current for the Hβ line in filament A is 6×10^{-12} A, which, allowing for $0^m\cdot3$ of interstellar absorption and $0^m\cdot3$ of atmospheric absorption would give a total radiated energy at 500 pc (the assumed distance of Vela X; see Milne 1968) of 3×10^{31} erg sec^{-1} in the Hβ line.

From Parker (1964*a*) the collisionally excited Hβ volume emissivity at $T_e = 10^4$ °K is $1\cdot5\times10^{-27}\,n_e n_H$ erg cm^{-3} sec^{-1} and $1\cdot88\times10^{-25}\,n_e n_H$ erg cm^{-3} sec^{-1} at $T_e = 2\times10^4$ °K, which when equated to the observed Hβ energy would yield values for $n_e n_H V$ of 2×10^{58} cm^{-3} and $1\cdot6\times10^{56}$ cm^{-3}, where V is the emitting volume. If m_H is the mass of the hydrogen atom, then $m_H n_H V$ is the mass of the emitting region. Therefore we can say that the emitting mass lies between $3\cdot4\times10^{34}/n_e$ and $2\cdot7\times10^{32}/n_e$ grams for an electron temperature between 10^4 and 2×10^4 °K respectively. Furthermore, we estimate that only 1/20 of the filament was in the entrance slit of the scanner. Allowing for this and for an electron density of 300 cm^{-3} (as in Section III), we find that the total visible mass of filament A lies between 1 and 10^{-2} solar mass.

Returning to the values for $n_e n_H V$ (2×10^{58} cm^{-3} at $T_e = 10^4$ °K, and $1\cdot6\times10^{56}$ cm^{-3} at $T_e = 2\times10^4$ °K), if all the electrons are from the ionization of the hydrogen, we can substitute n_e/f for n_H, where f is the ionization fraction ($= 2\cdot4\times10^{-3}$ at $T_e = 10^4$ °K, and $0\cdot928$ at $T_e = 2\times10^4$ °K; Parker 1964*a*), and using $n_e = 300$ cm^{-3}, as before, we arrive at emitting volumes of 5×10^{50} and 20×10^{50} cm^3 for $T_e = 10^4$ and 2×10^4 °K respectively. Estimating the length of filament A to be 1 pc we would have cross sectional areas of $1\cdot5\times10^{32}$ and 5×10^{32} cm^2. There are two feasible models for the filaments in these objects: (1) the circular filament model and (2) the "sheet-seen-edge-on" model. The radius arrived at if model (1) is assumed is $0\cdot7$–$1\cdot26\times10^{16}$ cm, whilst if model (2) is adopted and a depth is taken equal to its length then the width would be $4\cdot4$–15×10^{13} cm. It has been found that the narrowest filaments in supernova remnants have a width of about 2×10^{16} cm (Harris 1962), and in fact for filament A the thickness appears to be more like 10^{17} cm—a thickness that would support a circular model for filament A. The mass and volume were obtained for filament B in a similar manner, and they are almost identical with those of filament A.

V. Conclusions

We have shown that electron temperature stratification exists for two filaments of Vela X. This is not a newly discovered feature for objects of this type. Parker (1964*b*) used such a stratification to explain physical conditions in other supernova remnants, concluding that the temperature for the Cygnus Loop was $1 \cdot 7 \times 10^4$ °K from the lower excitation lines and near 10^5 °K from the [OIII] lines with similar behaviour evident in other remnants. It was Parker's conclusion that physical conditions do not change greatly from filament to filament and that the greatest gains could be obtained by making very intensive measurements of one or two filaments in an object and extending the conclusions to other filaments in the object.

We have suggested that the mass of an individual filament could be as high as a solar mass (which means that the total mass could be as high as 30 $M_{\odot}$) provided the temperature is, as we have measured it from the H, OII, and NII lines, near 10^4 °K. These "visible" masses are higher than have previously been obtained for objects of this type and are a direct outcome of the lower electron temperature found in these filaments. The upper limit obtained for the mass does in fact approach the mass that one would expect to be swept up by the expansion of this object to its present size. Whilst an argument is presented in favour of the circular filament model, which seems to be physically less likely than the "sheet-seen-edge-on" model, it is not easy to explain the stratification in the electron temperature in filaments of circular section. The detection of stratification may be an argument in favour of the sheet model.

V. Acknowledgments

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